The Impact of Episodic Events on Nearshore-offshore Transport in the Great Lakes: Hydrodynamic Modeling Program

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This proposal is written in response to the NSF/OCE and NOAA/COP Announcement of Opportunity for Coastal Studies in the Great Lakes. It is part of a multi-proposal, multidisciplinary program on the impact of episodic events on the coastal ecosystem in the Great Lakes. This proposal focuses on the hydrodynamic modeling. It was developed in close collaboration with the Physical Oceanography Program (Saylor et al.), so it shares some parts of the Introduction and Background sections with that proposal.

Introduction

In the Great Lakes, as well as in the coastal ocean, the gradients of many biogeochemically important materials (BIMs) are considerably higher in the offshore direction than in the longshore direction (Brink et al., 1992, Scavia and Bennett, 1980). In the presence of these large gradients, cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters and is one scientific focus of the NSF/OCE NOAA/COP initiative. As with most coastal environments where tidal currents are negligible, the mean alongshore transport in coastal regions of the Great Lakes is typically much larger than the cross-isobath component (Csanady, 1982). However, both the alongshore and cross-isobath components of the current exhibit strong episodic behavior due to wind forcing. Alongshore transport has been the major focus of previous large physical oceanography studies in the Great Lakes, including the International Field Year for the Great Lakes in 1972 (Saylor et al., 1981), the Lake Erie Binational Study (Boyce et al., 1987), and the Lake Ontario 1982-83 circulation study (Simons and Schertzer, 1989). As opposed to alongshore transport, the advective and diffusive mechanisms driving cross-shore transport and the time scales over which they operate have not been as extensively studied are not well understood. A necessary step in understanding cross-shore transport of BIMs is to identify and quantify the physical processes that are responsible for the nearshore-offshore water mass and material exchange.

Considerable progress has recently been made in developing two and three dimensional circulation models for the Great Lakes. Numerical hydrodynamic models are now able to simulate large scale circulation in the lakes with reasonable accuracy (Schwab and Bedford 1994, Schwab et al. 1996). Prospects are good in the near future for resolving kilometer scale variability in current and temperature fields with high resolution models. We believe that these models will be a useful tool in conjunction with a well-designed observational program for quantifying nearshore-offshore transport of water masses and suspended and dissolved constituents in the Great Lakes. The models can also be used to help design effective sampling programs for physical, chemical, and biological parameters by identifying critical regions and time periods for significant cross-isobath transport, i.e., regions and periods that exhibit the critical combination of 1) significant inshore/offshore gradient of a particular parameter, and 2) episodes of cross-isobath transport.

In the context of nearshore-offshore transport, the Great Lakes present somewhat different challenges than the continental shelf. Although many of the physical processes responsible for the movement of material from the coastline toward deeper waters are similar in both regimes, the fact that the lakes are fully enclosed by land has significant consequences. When material is transported offshore in the Great Lakes, it can only be removed from the system by permanent burial in the sediments or removal through an outflow. This is in contrast to the continental shelf where transport across the shelf break to the deep ocean can also be considered a removal mechanism. The physical mechanisms for cross-shelf transport are similar, and in some cases identical, to the processes that control nearshore-offshore transport in the lakes, but there is no analogue in the lakes for exchange with the deep ocean across the shelf break. The purpose of this proposal is examine the physical mechanisms primarily responsible for nearshore-offshore transport of BIMs in the lakes.

Recent satellite observations of suspended sedimentary material in Lake Michigan (Fig. 1, Eadie et al., 1996) offer a unique opportunity to investigate a recurrent episode of cross-isobath transport. A 10 km wide plume of resuspended material extending over 100 km along the southern shore of the lake was first observed in satellite imagery by Mortimer (1988), and has since been observed every spring since 1992, when satellite imagery for the Great Lakes region first became available on a routine basis through the NOAA CoastWatch program (Schwab et al., 1992). The onset of the plume appears to be correlated with the disappearance of ice from the lake and a major storm with strong northerly winds, although there is evidence that this event can occur later in the year (Mortimer, 1988). The plume is apparent along the entire southern coastline of the lake. It occasionally veers offshore along the eastern shore of the lake, coincidentally near the areas of highest measured long-term sediment accumulation in the lake (Fig. 1). The offshore structure of the turbidity plume often resembles the structure of cold water filaments seen in thermal imagery of the California Current by Strub et al. (1991) and others. We believe this type of event is ideal for studying the physical processes controlling cross-isobath transport of BIMs in the Great Lakes, and in Lake Michigan in particular.

Present State of Knowledge

Climate and thermal cycle of the Great Lakes

The physical dimensions of the Great Lakes (horizontal length scales of hundreds of kilometers, maximum depths of 200-400 meters except for Lake Erie) are similar to dimensions of continental margins, and many of the same physical processes occur in both areas. In contrast to the continental shelf, the Great Lakes exhibit a pronounced annual thermal cycle (Boyce et al., 1989). By the end of fall, the lakes are usually become vertically well-mixed from top to bottom at temperatures near or below the temperature of maximum density for freshwater, about 4 degrees C. Further cooling during winter can lead to inverse stratification, and ice cover. Springtime warming tends to heat and stratify shallower areas first leaving a pool of cold water (less than 4 degrees C and vertically well-mixed because of convection) in the deeper parts of the lake. In spring, stratified and homogeneous areas of the lake are separated by a sharp thermal front, commonly known as the thermal bar. Depending on meteorological conditions and depth of the lake, the thermal bar may last for a period of from 1 to 3 months.

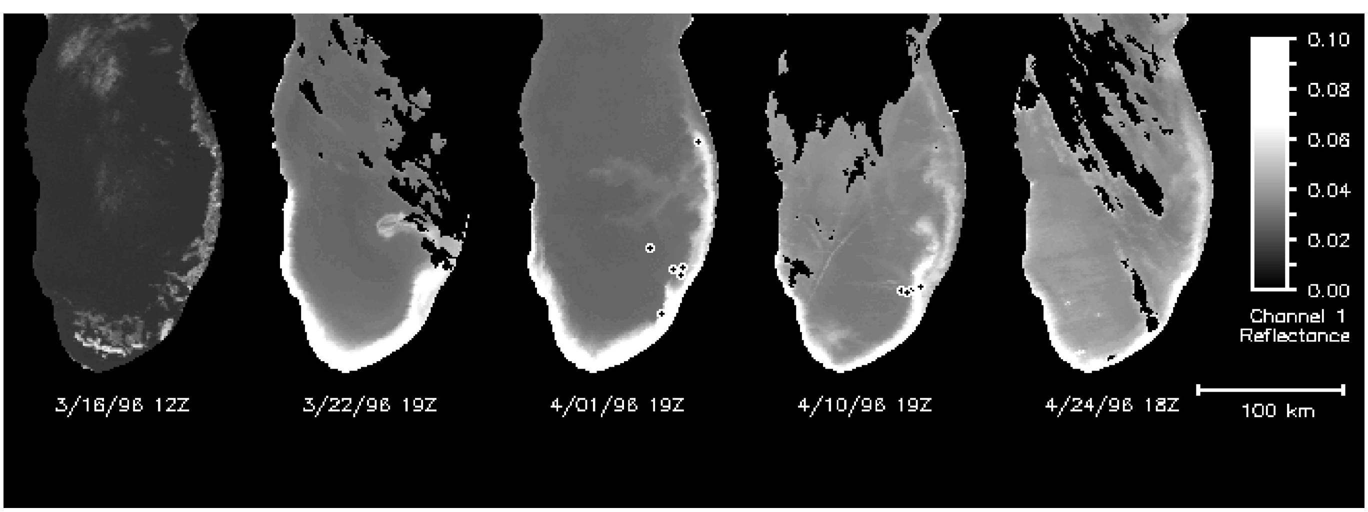

Figure 1. AVHRR channel 1 (visible) imagery of the 1996 Lake Michigan plume.

Stratification eventually covers the entire lake, and a well-developed thermocline generally persists throughout the summer. In the fall, decreased heating and stronger vertical mixing tend to deepen the thermocline until the water column is again mixed from top to bottom. When the nearshore surface temperature falls below the temperature of maximum density, the fall thermal bar starts its propagation from the shoreline toward the deeper parts of the lake. Thermal gradients are much smaller during this period than during the springtime thermal bar.

Because of their mid-latitude position, the Great Lakes are subject to periodic extratropical storms, particularly during the spring and fall periods when the jet stream is crossing these latitudes. Typical intervals between storms are 5-7 days during winter and 7-10 days during summer. Storms can rapidly generate strong currents which decay with time scales of several days. The spatial scales of extratropical cyclones are only a little larger than the dimensions of the lakes, often resulting in considerable nonuniformity in the wind fields across a lake. The spatial variability of the wind field can have considerable influence on the resulting circulation pattern in the lake. Figure 2 from Schwab and Bennett (1987) shows wind stress and current energy in Lake Erie for 6 months in 1979. The episodic nature of atmospheric forcing and the lake's response is clear.

Great Lakes ice cover and ice transport

Ice cover can cause significant changes in waves and winter circulation patterns in a large lake. The Great Lakes are usually at least partially covered with ice from December to April. Initially, ice begins to form in shallow bays, and then gradually grows offshore. Maximum ice extent is normally observed in late February, when ice typically covers from 24% of Lake Ontario to 90% of Lake Erie (Assel et al, 1983). During that period, ice typically covers 45% of Lake Michigan. Ice thickness can vary from a few centimeters to a meter or more (Rondy, 1976). Ice melting and break up usually begins in March when increasing solar radiation weakens the ice which can be more easily broken up by the action of wind and waves. In some mild winters, ice may be gone from the southern Lake Michigan on January or February. In severe winters, it may last until the end of March.

Very little is known about ice transport in the Great Lakes. Measurements of ice movement in Lake Erie (Campbell et al., 1987) by means of drifting buoys still represent the most significant source of information on wind-induced ice dynamics in the Great Lakes. In particular, they reported the mean observed speed of the buoys in ice is about 8 cm/s, half the mean speed observed in the open water of Lake Michigan. The first numerical model of ice transport in the Great Lakes was developed by Rumer et al. (1981). It was based on Hibler's dynamic-thermodynamic sea-ice model (Hibler, 1979), but used a very simple circulation model. The model showed some success when applied to Lake Erie. Recently, Wang et al. (1994) simulated quite realistically the ice dynamics in Hudson Bay by applying Hibler's

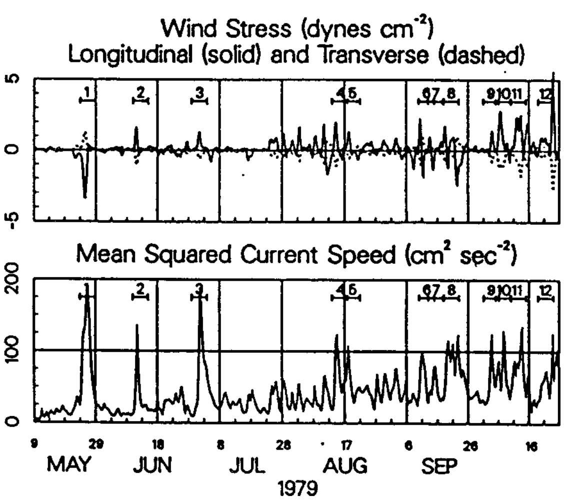

Figure 2. Example of wind-driven episodic currents in the Great Lakes.

model coupled with the three-dimensional hydrodynamic model of Blumberg and Mellor (1987).

Circulation in the Great Lakes: longshore and offshore transport

Wind-driven transport is a dominant feature of circulation in the lakes. In addition to the spatial and temporal variability of the wind forcing, the earth's rotation, basin topography, and vertical density structure are all important influences in the dynamical response of the lake. As shown by Bennett (1974), Csanady (1982), and others, the response of an enclosed basin with a sloping bottom to a uniform wind stress consists of longshore, downwind currents in shallow water, and a net upwind return flow in deeper water. The streamlines of the flow field form two counter-rotating closed gyres (Fig. 3a, Saylor et al., 1980), a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left (in the northern hemisphere). In this classic two gyre pattern, there are two points along the shoreline where cross isobath transport occurs, one on the upwind shore where diverging longshore currents are accompanied by onshore flow, and one on the downwind shore where converging longshore currents are accompanied by offshore flow. As the wind relaxes, the two-cell streamline pattern rotates cyclonically within the basin (Fig. 3a-c.), with a characteristic period corresponding to the lowest mode vorticity wave of the basin (Saylor et al., 1980). For a Coriolis parameter and geometry representative of the Great Lakes, this period is on the order of 3-5 days, closely corresponding to the periodicity of storm forcing. Numerical models approximating actual lake geometry have proven to be remarkably effective in explaining observed circulation patterns in lakes (Sheng et al., 1978, Simons, 1980, Schwab 1983, Murthy et al., 1986, Schwab and Bennett 1987). The results of these modeling exercises show that the actual bathymetry of each of the Great Lakes tends to act as a combination of bowl-shaped sub-basins, each of which tends to support its own two-gyre circulation pattern.

Besides bathymetry and geometry, two other important factors tend to complicate the simple lake circulation model described above, namely nonuniform wind forcing and stratification. The effect of horizontal variability in the wind field enters through the curl of the wind stress field (Rao and Murthy, 1970, Strub and Powell, 1986). Any vorticity in the forcing field is manifest as a tendency of the resulting circulation pattern toward a single gyre streamline pattern, with the sense of rotation corresponding to the sense of rotation of the wind stress curl. Coupled with stratification, wind stress curl can also contribute to the formation of frontal features and upwelling zones (DeSzoeke, 1980, DeRuijter, 1983). Because of the size of the lakes, and their considerable heat capacity, it is not uncommon to see lake-induced mesoscale circulation systems superimposed on the regional meteorological flow, a meso-high in the summer (Lyons, 1971) and a meso-low in the winter (Petterssen and Calabrese, 1959). As mentioned above, there can also be a considerable amount of vorticity imparted to the lake by the normal circulation pattern of an extratropical storm as it passes over the lake. In either case, the two-gyre lake circulation pattern set up by a uniform wind can be distorted or overwhelmed completely by the curl of the wind field.

Spring and summer stratification in the lakes adds a baroclinic component to the lake circulation. Thus, during the thermal bar period, longshore currents frequently form a single cyclonic gyre circulation pattern driven by onshore-offshore density gradients. It is also possible that cross-isobath transport may be induced by the vertical circulation cells accompanying the thermal bar as it moves slowly from shore toward the deeper part of the lake, but the magnitude of this effect would be much smaller than storm-induced transport. Another physical process that contributes to offshore transport during summer is upwelling. During the period of stratification, significant wind events will cause upwelling of the thermocline along the shore. Upwelling generally occurs on the upwind shore and

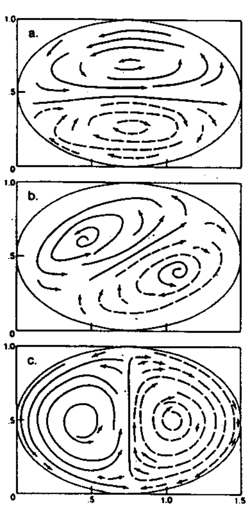

Figure 3. Two-gyre vorticity wave in a circular paraboloid.

the shore to the left of the wind direction, as discussed by Csanady (1982). These wind forcings, directly or through Ekman drift, move surface water away from the shore, so that it must be replaced by colder upwelled water. In Lake Michigan, because of its north-south orientation, the greatest upwelling is along the eastern shore resulting from northerly winds, and along the western shore resulting from southerly winds. The scale of the offshore distance over which this upwelling takes place depends on the wind stress and near-shore bathymetry, and is typically on the order of 5-10 km.

All of the mechanisms discussed above can generate cross-isobath currents, however their relative importance to the short-term (episodic) and long-term (seasonal) transport of BIMs is not known. The Lake Michigan experiment described here will allow us to examine and compare the physical processes most important to cross isobath transport.

Hydrodynamic modeling of the Great Lakes with the Princeton Ocean Model

There has been significant progress in hydrodynamic modeling, especially in modeling short-term processes such as water level fluctuations due to seiches or storm surges with two-dimensional models in the Great Lakes (Schwab, 1992). Nowadays, with increases in computer power, a whole new set of environmental problems can be addressed using three-dimensional hydrodynamic modeling. Many oceanographers and limnologists have used the Princeton Ocean Model (POM) of Blumberg and Mellor (1987) in the ocean, coastal areas, and lakes. In particular, over the past 5 years, POM has been adapted for use in the Great Lakes and has been successfully applied to Lake Erie as part of the Great Lakes Forecasting System (Schwab and Bedford 1994), and Lake Michigan (Schwab et al, 1996; Beletsky et al, 1997c). Examples of POM results for Lake Erie are available on the World Wide Web (WWW) at the address *http://superior.eng.ohio-state.edu.* The Princeton model is also being used in the EPA-sponsored Lake Michigan Mass Balance Study (Beletsky et al, 1997a, Beletsky et al, 1997b). In this study, the hydrodynamic model of Lake Michigan has 20 vertical levels, and uniform horizontal grid size of 5 km. The model output is being used as an input for sediment transport and water quality models to study the transport and fate of toxic chemicals during 1994 -1995. The model was extensively calibrated using an excellent set of observational data during 1982 - 1983, including water level observations from 9 gauges around the lake, surface temperature observations at two permanent buoys, and current and temperature observations from 15 subsurface moorings. The model was able to reproduce realistically main features of thermal structure and large-scale circulation of Lake Michigan (Fig. 4).

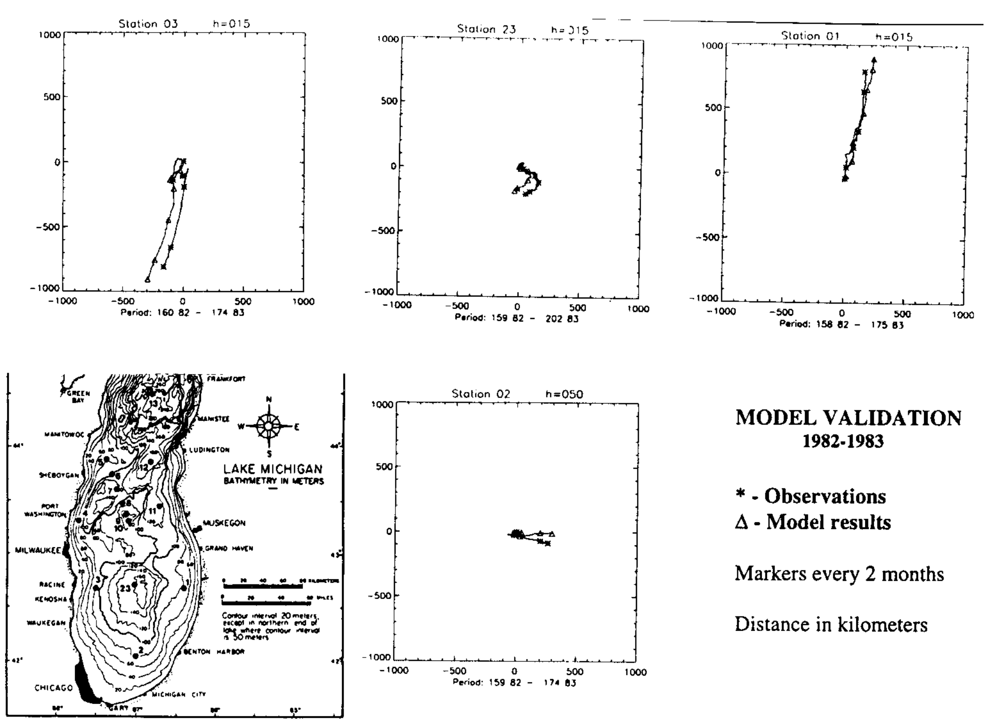

Figure 4. Progressive vector diagrams (summer 1982 -summer 1983) of observed (triangles) and computed (stars) currents at 15 m depth at four moorings in Southern Lake Michigan. Location of moorings is shown on the left lower panel.

Hypothesis

We believe that one of the most favorable times for biogeochemically significant cross-margin transport in Lake Michigan is the late winter/early spring period. Input from tributaries is highest during this period, significant resuspension of nearshore bottom sediment is common, and nearshore thermal gradients can be large. In addition, spring storms provide energetic impulses to lake circulation patterns, resulting in episodic occurrences of strong cross-isobath transport. Northerly winds brought by these storms also generate significant waves causing massive resuspension of sediments in southern Lake Michigan, and subsequent transport of material offshore. Earlier in the season the strength of such events is probably diminished by the presence of ice which protects a pool of fine-grained sediments in southern Lake Michigan from resuspension (Fig. 5). ***It is our hypothesis that the forced, two-gyre vorticity wave response of the lake to episodic wind events, occasionally modified by stratification, is a major mechanism for nearshore-offshore transport in the Great Lakes.*** Our hydrodynamic modeling program is designed to test this hypothesis through the application of numerical models, testing them against direct observations of currents in the study area (see proposals of Saylor et al., and Vesecky), and assessing the dynamic mechanisms responsible for nearshore-offshore transport.

Objectives

The main objective of this proposal is to identify and quantify the physical processes generating nearshore- offshore transport of biogeochemically important materials in the Great Lakes during episodic events by applying a coupled ice-circulation model to Lake Michigan. We will use the annual turbidity plume in Lake Michigan as a tracer to reveal nearshore-offshore circulation patterns. We will also interact with the other components of the program to assess the impact of nearshore-offshore transport on sedimentary processes and biological processes.

Our specific objectives are:

- To determine the role of ice in timing and magnitude of the plume events.
- To determine whether the plume occurrence represents a response to the aggregate effects of a season of individual storm events, an episodic response to a single large storm event or a complex interaction between the low-frequency (seasonal) preconditioning of the lake and a single storm event that occurs at a critical time.[1]
- To determine the importance of mesoscale atmospheric dynamics on the development of the plume.[1]
- To determine the role of local bathymetry in the separation/meandering of the plume.
- To determine the influence of thermal effects on the dynamics of the plume.
- To refine the ice and circulation models using the results of an extensive observation program.[2]
- To link the ice-circulation model and the Lake Michigan wind wave prediction model with a sediment resuspension/transport model in order to quantify the cross-isobath transport of resuspended material in the lake. [3]
- To link the ice-circulation model with a nutrient and lower food web model in order to investigate the impact of nearshore-offshore transport during episodic events on biological processes in the lake.[4]
- To incorporate the results of these investigations into a computer-based Information and Forecasting System.

[1]in collaboration with the Meteorological Modeling proposal of Roebber.
[2]in collaboration with the Physical Oceanography proposal of Saylor et al., the HF Radar Observations proposal of Vesecky, and the Retrospective Remote Sensing Analysis of Budd et al.
[3]in collaboration with the Sediment Transport Modeling proposal of Bedford and McDonald.
[4]in collaboration with the Lower Food Web Modeling proposal of Chen.

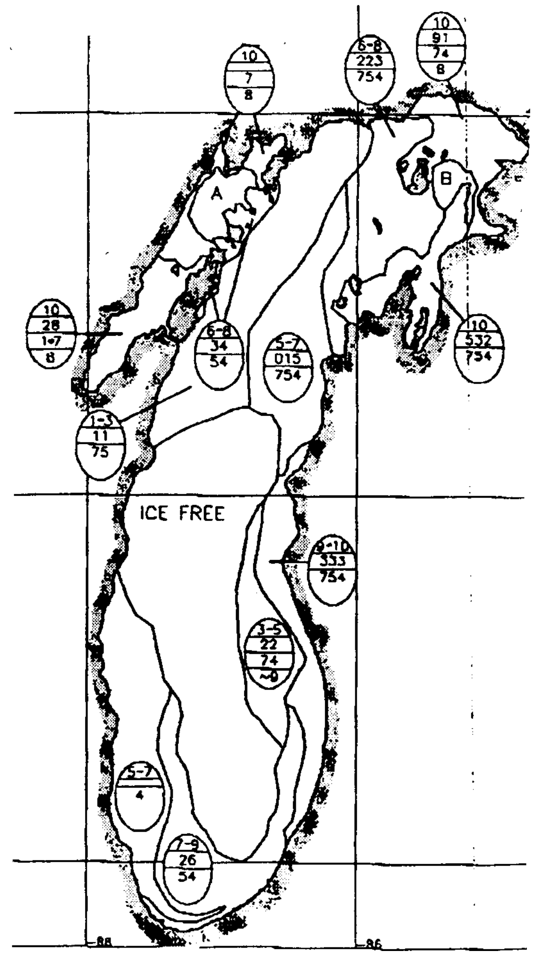

Figure 5. Lake Michigan ice cover on March 11, 1996, one week before the plume event.

Approach

The recurrent springtime appearance of an extensive turbidity plume in southern Lake Michigan (Eadie et al. 1996) provides us with the opportunity to examine the two-gyre vorticity wave hypothesis during a period when the large volume of suspended material can act as a natural tracer for lake circulation. We plan to exploit this opportunity by concentrating our modeling program on the Lake Michigan plume. Based on experience gained both in previous observations (Saylor et al, 1980), circulation modeling (Schwab, 1983), and recent observations (Eadie et al, 1996), Saylor et al. designed an array of moorings in the vicinity of a bathymetric hump near St. Joseph, Michigan. This is the region where separation of the plume occurs most frequently, and hence the most significant cross-margin transport occurs. The moored instrument array, together with Lagrangian measurements, CTD surveys, and HF radar current measurements will be used to determine how accurately the hydrodynamic model simulates the location of major cross-margin transport, and its magnitude. Therefore, their observations will be essential for model validation and improvement.

Hydrodynamic model results will be coupled with sediment resuspension/transport/deposition models and lower food web models to estimate the transport and fate of many types of biogeochemical materials (nutrients, sediments, toxics). To identify the critical physical processes involved in offshore (and longshore) transport of BIMs and to develop predictive ability for management and control strategies we propose a four-part modeling program.

1. Ice Modeling

Our previous experience with the Princeton Ocean Model was quite successful in describing winter circulation in Lake Michigan in two very mild winters: 1982-1983, and 1994-1995, when the lake was essentially ice-free (Beletsky et al. 1997a, Beletsky et al. 1997b). To study plume events in years with significant ice cover, we plan to use a numerical ice dynamics model. The model was developed by Stubblefield and Bennett (1984) at GLERL, and is a modified version of the model by Rumer et al. (1981). The model predicts the motion of ice in response to the action of wind, currents, Coriolis force, gravitational force, and internal ice stresses. The model uses viscous-plastic constitutive law proposed by Hibler (1979). Modeling ice in lakes is different from that in the ocean because of the significance of ice growth and melting. Presently, the model does not include thermodynamic factors which will be especially important for correct simulation of ice melting before the occurrence of the turbidity plume. We are planning to incorporate these effects to have a fully coupled dynamic thermodynamic ice-circulation model, which is a significant improvement over the Stubblefield and Bennett (1984) model. We are planning to use the routine (2-3 times per week) ice observations for the Great Lakes from the National Ice Center for the purpose of model calibration and validation.

2. Circulation Modeling

We will apply a lake-scale hydrodynamic circulation model (the Great Lakes version of the Princeton Ocean Model, Blumberg and Mellor 1987) to Lake Michigan for the selected periods in 1992-1997 during which the springtime turbidity plume has been observed, and for the program's field years. The model is based on the three-dimensional, nonlinear Navier-Stokes equations. It employs a terrain-following vertical coordinate (sigma coordinate) to provide high vertical resolution even in shallow areas, and the Mellor and Yamada (1982) turbulence closure scheme.

The hydrodynamic model will be coupled with the ice model using the same horizontal grid. Retrospective analysis of visible imagery planned in the proposal of Budd et al. will help to determine which periods will be chosen for model simulations. Our previous experience with multi-year modeling of Lake Michigan thermal structure showed that the model always performed better during the second model year, because inherent errors in the initial temperature field in the first model year were gradually filtered out by model adjustment to boundary conditions. Therefore, for the program field years the model will be run through the whole year, without interruption, to improve heat fluxes from water to ice, and hence improve the ice modeling.

We will use the hydrodynamic model to calculate the three-dimensional current and temperature fields in the lake on a 2 km horizontal grid (Fig. 6) in order to be able to resolve both the coastal boundary layer and currents within the plume (whose width is about 5-10 km according to a satellite imagery). Fine resolution of the coastal boundary layer is important because the majority of resuspension, again according to a satellite imagery, occurs within 10-15 km distance from the coast (Fig. 1). Therefore, some experiments will also be carried out with higher (1 km) horizontal resolution, to study how improved horizontal resolution will influence velocity field and eventually sediment resuspension and transport (see Bedford and McDonald proposal) during episodes of strong wind forcing. Model bathymetry will be based on the new, high resolution bathymetric data recently released by the National Geophysic Data Center (NGDC, 1996). For the Lake Michigan study, we expect to be able to use from 20 to 30 vertical levels. Vertical levels will be spaced closer near the bottom and near the surface to better resolve boundary layer processes there.

For these simulations, meteorological data from National Weather Service surface observing stations and two mid-lake weather buoys will be used to synthesize overwater momentum flux and heat flux fields to drive the model. Previous applications of the circulation model have shown that the accuracy

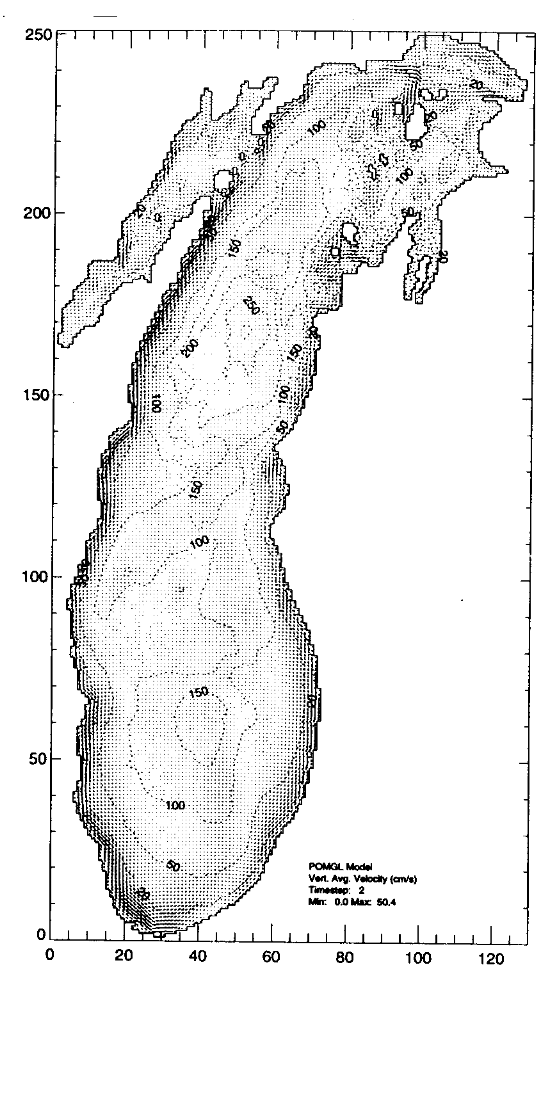

Figure 6. Depth-averaged currents in Lake Michigan calculated with POM. Initial response to an idealized northerly wind. Barotropic case, 2 km grid.

of the results is often limited by the accuracy of the forcing fields (Schwab 1983, Schwab and Bennett 1987, Schwab et al. 1989, O'Connor and Schwab 1994). Therefore, we will also use output from the high resolution meteorological model (MM5, Dudhia, 1993) described in Roebber's proposal to test the limitations of meteorological fields derived from the surface observation network. In particular, we are planning to use MM5 output from 54, 18 and 6 km grids to determine the influence of mesoscale atmospheric dynamics on the circulation and development of the plume (this will be done in collaboration with Bedford and McDonald). In addition, high resolution wind direction observations by the multifrequency HF radar in the study area (see proposal by Vesecky) will be assimilated into MM5 output. To determine whether the plume occurrence represents a response to the aggregate effects of a season of individual storm events, an episodic response to a single large storm event or a complex interaction between the low-frequency (seasonal) preconditioning of the lake and a single storm event that occurs at a critical time, we will carry out a set of scenario testing experiments. For example, to test the importance of aggregate effects alone we will force the ice-circulation model with climatological momentum and heat fluxes (say, monthly averages), and see if any plume develops in the spring. To test the significance of a single storm, we will run the model with meteorology modified by replacing the actual storm with weaker versions of the storm, or move the storm event in time.

Several other scenario testing experiments will also be carried out to determine the role of different factors in the plume dynamics. To determine the role of ice in timing and magnitude of the plume events, we will compare model results with and without ice cover. To determine importance of thermal effects, especially during the thermal bar period, we will compare model results with and without temperature gradients. To determine importance of local bathymetry in separation/meandering of the plume, we will compare model results with actual bathymetry and with an artificial bathymetry in which the hump in the area of observations will be removed. If necessary, some experiments will also be carried out in basins with idealized bottom topography and simplified atmospheric forcing. Model output will be analyzed to determine the principal physical processes governing cross-isobath transport. Possible processes contributing to offshore transport include barotropic return flow during storm events and Ekman drift, topographically induced flow separation and recirculation of coastal currents, and baroclinic processes such as the thermal bar, upwelling, and baroclinic instability of coastal currents.

We will compare surface water temperature fields calculated by the model for the field seasons to NOAA satellite-derived surface temperature fields available through the NOAA CoastWatch program at GLERL (Schwab et al. 1992). We will compare surface currents calculated by the model to those derived from a multifrequency HF radar observations described in the proposal by Vesecky. We will also calculate trajectory statistics using model results, and compare them with those of drifter buoys. To refine existing model parameterizations, model results for currents and temperatures will be compared to observational data from ship surveys, current meters, and thermistor arrays deployed during the field years as part of the program (Fig. 7). In particular, several CTD surveys, five thermistor chain moorings, and ADCP data from six moorings will provide detailed information on the evolution of vertical current and thermal structure. This information will be essential for testing the Mellor-Yamada (1982) turbulence parameterization scheme presently used in the model. We will test the Mellor-Yamada scheme during the periods of strong temperature gradients (thermal bar period, for example), and if necessary replace it with a more refined scheme, like recently suggested by Kantha and Clayson (1994), or another advanced scheme.

Calculations will be carried out on high speed workstations at GLERL (HP9000 K-200 4 processor SMP, and HP9000 C-160).

3. Wave Modeling

A parametric wave model for the Great Lakes developed by Schwab et al. (1984) will be used to provide estimates of wave characteristics for use in sediment resuspension calculations. This model has

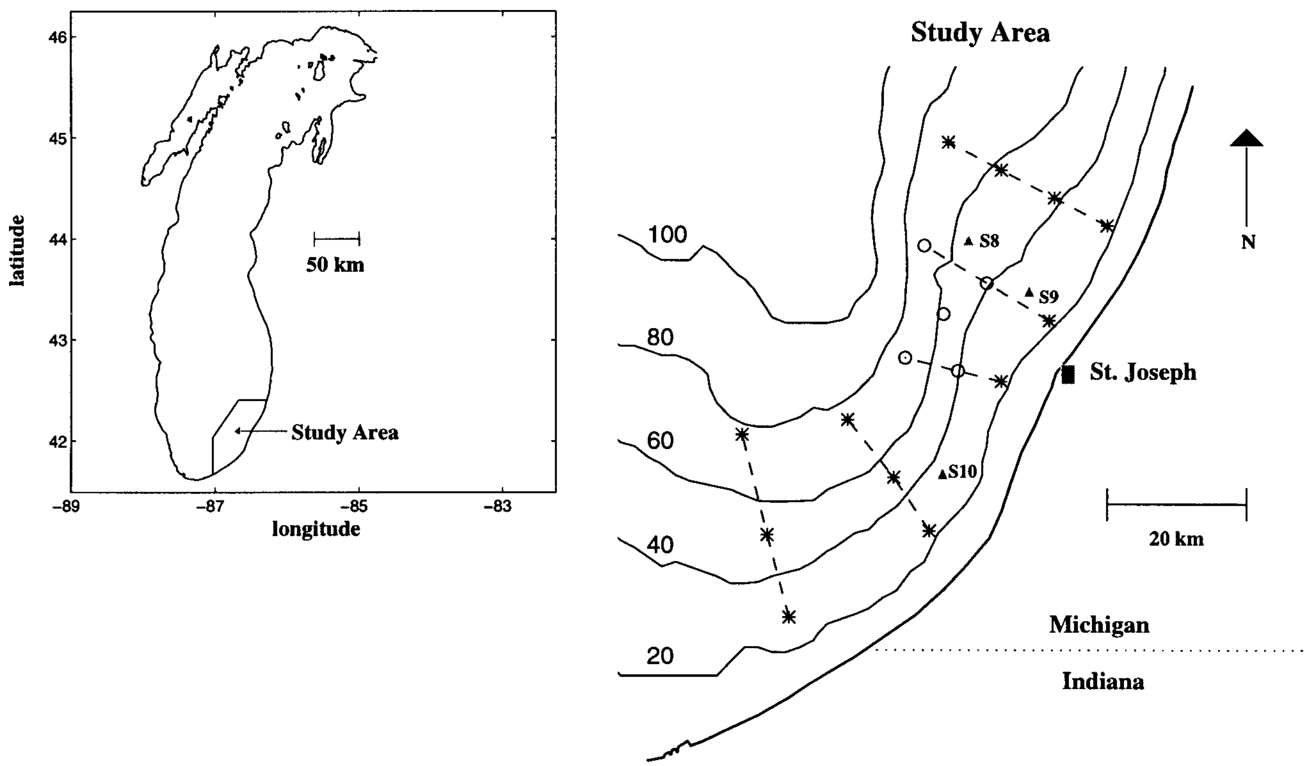

Figure 7. Moored arrays. Open circles are ADCP current meters, stars are VACM current meters.

been shown to provide excellent estimates of significant wave height and wave direction for fetch-limited waves (Liu et al., 1984) , but has a tendency to underestimate wave periods. Multifrequency HF radar observations of waves described in the proposal by Vesecky will be compared with model results. We plan to examine the empirical relations between nondimensional wave height and wave period in the model to see if the accuracy of the wave period estimates can be improved.

4. Integration with Sediment Transport Modeling and Lower Food Web Modeling Projects

Currents, temperatures, and turbulence characteristics will be used as input to the sediment and particle transport models, and lower food web models being developed at in related proposals. In particular, a version of the sediment transport model developed by Ziegler and Lick (1988) will be incorporated into the hydrodynamic modeling framework so that results of the hydrodynamic model simulation can be used to drive sediment resuspension/transport/ deposition model calculations using the same numerical grid and bathymetry. This model will be applied by Bedford and McDonald to the project field years and selected retrospective cases using the best available data on sediment distribution and source regions as boundary conditions.

A simple lower food web model (basic nutrients, phytoplankton, and zooplankton) will also be incorporated into the hydrodynamic modeling framework. This activity will be a collaborative effort with Changsheng Chen, whose proposal is being submitted as part of this program. The food web model will be applied at the same grid resolution as the hydrodynamic model. For the food web model we will also supply short-wave radiation as part of meteorological filed prepared for the hydrodynamic modeling.

Work Schedule

We consider the hydrodynamic modeling program an essential, integrating part of the whole experiment. It serves as a foundation for sediment resuspension and transport modeling, and lower food web modeling. The information needed to drive the ice-circulation model of Lake Michigan will be available on a regular basis as the experiment goes on. Therefore, we will be able to start model runs with a delay of only a few months relative to the field observations. We will spend time in the beginning of the experiment for modification of the ice model, and coupling it with the hydrodynamic, sediment transport, and lower food web models, preparation of meteorological fields, and retrospective modeling of selected plume events. Details are presented in the work schedule:

Year 1 (6 months). Development of the thermodynamic part of the ice model, its testing and calibration.

Year 2 (12 months). Coupling circulation and ice models. Meteorological data preparation and analysis. Retrospective analysis and simulation (selective events during 1992-1997, and pilot year. Linking circulation-ice model with sediment transport and lower food web models.

Year 3 (12 months). Meteorological data preparation and analysis. Modeling and analysis of the first field year. Comparison with observations. Publications.

Year 4 (12 months). Meteorological data preparation and analysis. Modeling and analysis of the second year. Comparison with observations. Publications.

Year 5 (12 months). Meteorological data preparation. Scenario testing modeling and analysis. Model refinement. Final analysis. Publications.

Products

Three-dimensional fields of currents, temperature, turbulence coefficients, and two-dimensional fields of surface elevation, ice thickness, ice compactness, ice velocity, wave height, wave period and wave direction calculated for the field years, and selected periods during 1992-1997 will be available for all programs. Particle trajectories calculated on the basis of model results will also be made available. We plan to provide several types of graphics, including animations of model results, as well as numerical data. This information will be used in the sediment resuspension and transport model, and lower food web model, and also for the interpretation of chemical and biological observations.

Refined ice and circulation models will be a result of a comparison of model simulations and extensive observational program.

The refined ice model will be incorporated into the Great Lakes Forecasting System for routine predictions of ice compactness, depth, and ice drift in the Great lakes.

Significance

We expect that the hydrodynamic modeling program, employing state of the art numerical models for circulation, waves, and ice, in close collaboration with the observational program, will provide significant insight into the mechanisms of cross-margin transport in the Great Lakes, and semi-enclosed seas. Winter circulation in the Great Lakes will be studied for the first time with the coupled ice-circulation model. The ice-circulation model will be coupled with the sediment resuspension and transport model, and the lower food web model on a fine resolution grid, which will lead to better understanding of the response of the Great Lakes ecosystem to the impact of natural and anthropogenic stressors.

Relevant Experience Related to Proposal

Dr. Schwab has worked on geophysical fluid dynamics problems in the Great Lakes since 1974, including theoretical and observational investigations of barotropic and baroclinic seiches, storm surges, wind waves, circulation patterns, and overwater wind stress. In the past 5 years, he has directed the adaptation and testing of the Princeton Ocean Model (POM) for the Great Lakes. The adapted model is being used in the Great Lakes Forecasting System and the EPA Lake Michigan Mass Balance study.

The Great Lakes Forecasting System was developed by Dr. Schwab and Dr. Keith Bedford of Ohio

State University to provide real-time nowcasts and forecasts of the physical state of the Great Lakes. It was funded by NOAA-COP to serve as a prototype Coastal Forecasting System. Many of the methods for estimating overwater heat and momentum fluxes developed for this system continue to be part of the POM Great Lakes version. The application of the GLFS to Lake Erie provided extensive opportunity for validation of the applicability of POM to the Great Lakes.

In the last 3 years, Dr. Schwab has been PI for the Hydrodynamic Modeling project of the EPA-sponsored Lake Michigan Mass Balance Study. In this project, the Great Lakes version of POM was applied to a 5 km grid of Lake Michigan for two periods of two years (1982-83, 1994-95). The results of these simulations have also been extensively validated, and used in EPA water quality and sediment transport models. The present proposal will allow us to extend these results to the Lake MIchigan plume study, to examine more closely the physics of offshore transport in the plume region, and to couple an ice dynamics model with the Great Lakes POM.

Dr. Beletsky has studied thermal structure and circulation in large lakes since 1986, when he began to study the hydrodynamics of the two largest European lakes, Lake Ladoga, and Lake Onega using three-dimensional numerical models and measurements. His research was concentrated on the dynamics of upwelling fronts, wind-driven circulations, and thermal bars. He has studied hydrodynamics of Lake Michigan with the Princeton Ocean Model since 1994, working with Dr.Schwab on the problem of internal Kelvin waves, and later on the long-term modeling of circulation and thermal structure for the USEPA-sponsored Lake Michigan Mass Balance Project.

References Cited

Assel, R.A., Quinn, F.H., Leshkevich, G.A., and S.J. Bolsenga, 1983. Great Lakes Ice Atlas. National Oceanic and Atmospheric Administration.

Beletsky, D., K.K. Lee and D.J. Schwab. 1997a. Recent advances in hydrodynamic modeling of the Great Lakes. Proceedings of the XXVII IAHR Congress (In press).

Beletsky, D., W.P. O'Connor, and D.J. Schwab. 1997b. Hydrodynamic modeling for the Lake Michigan mass balance project, in G.Delic and M.F. Wheeler (eds), Next Generation Environmental Models Computational Methods, Proceedings of a U.S.EPA sponsored workshop at the National Environmental Supercomputing Center, August 7-9, 1995, Bay City, MI, SIAM, Philadelphia, PA, p.125-128.

Beletsky, D., W.P. O'Connor, D.J. Schwab and D.E. Dietrich. 1997c Numerical simulation of internal Kelvin waves and coastal upwelling fronts. J.Phys.Oceanogr.(In press).

Bennett, J.R., 1974. On the dynamics of wind-driven lake currents. J. Phys. Oceanogr. 4(3), 400-414.

Blumberg, A.F. and G.L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. Three dimensional Coastal Ocean Models, Coastal and Estuarine Sciences, 5, N.S. Heaps [ed.] Amer. Geophys. Union, Washigton, D.C., pp 1-16.

Boyce, F.M., M.N. Charlton, D. Rathke, C.H. Mortimer, and J.R. Bennett, 1987. Lake Erie Binational Study, 1979-1980. J. Great Lakes Res. 13(4), 840pp.

Boyce, F.M., M.A. Donelan, P.F. Hamblin, C.R. Murthy, and T.J. Simons, 1989. Thermal structure and circulation in the Great Lakes. Atmos.-Ocean, 27(4), 607-642.

Brink, K.H., J.M. Bane, T.M. Church, C.W. Fairall, G.L. Geernaert, D.E. Hammond, S.M. Henrichs, C.S. Martens, C.A. Nittrouer, D.P. Rogers, M.R. Roman, J.D. Roughgarden, R.L. Smith, L.D. Wright, and J.A. Yoder, 1992. Coastal Ocean Processes: a Science Prospectus. Rept. No. WHOI-92-18, Woods Hole Oceanographic Institution, Woods Hole, MA. 103.

Campbell, J.E., Clites, A.H., and G.M. Greene, 1987. Measurements of ice motion in Lake Erie using satellite-tracked drifter buoys. NOAA Data Report ERL GLERL-30.

Csanady, G.T., 1982. Circulation in the Coastal Ocean. D.Reidel Co., Dordrecht, Holland, 279pp.

DeRuijter, W.P.M., 1983. Frontogenesis in an advective mixed-layer model. J. Phys. Oceanogr. 13, 487-495.
DeSzoeke, R.A., 1980. On the effects of horizontal variability of wind stress on the dynamics of the ocean mixed layer. J. Phys. Oceanogr. 10, 1439-1454.
Dudhia, J., 1993: A nonhydrostatic version of the Penn State-NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front. Mon. Wea. Rev., 121, 1493-1513.
Eadie, B.J., D.J. Schwab, G.L. Leshkevich, T.H. Johengen, R.A. Assel, R.E. Holland, N. Hawley, M.B. Lansing, P. Lavrentyev, G.S. Miller, N.R. Morehead, J.A. Robbins, and P.L. Van Hoof, 1996. Anatomy of a recurrent episodic event: a winter-spring plume in southern Lake Michigan. EOS, Trans. Amer. Geophys. Union., 77, 337-338.
Hibler III, W.D., 1979. A dynamic thermodynamic sea ice model. J. Phys. Oceanogr. 9, 815-846.
Kantha, L.H., and C.A. Clayson, 1994. An improved mixed layer model for geophysical applications. J. Geohys. Res., 99, C12, 25235-25266
Liu, P.C., D.J. Schwab, and J.R. Bennett, 1984. Comparison of a two-dimensional wave prediction model with synoptic measurements. J. Phys. Oceanogr., 14(9), 1514-1518. Lyons, W.A., 1971. Low level divergence and subsidence over the Great Lakes in summer. Proc. 14th Conf. Great Lakes Res. Internat. Assoc. Great Lakes Res., 467-487.
Lyons, W.A., 1971. Low level divergence and subsidence over the Great Lakes in summer. Proc. 14th Conf. Great Lakes Res., Int. Assoc. Great Lakes Res., 467-487.
Mellor, G.L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., 20(4), 851-875.
Mortimer, C.H., 1988. Discoveries and testable hypotheses arising from Coastal Zone Color Scanner imagery of southern Lake Michigan. Limnol. Oceanogr., 33(2), 203-226.
Murthy, C.R., T.J. Simons, and D.C.L. Lam, 1986. Simulation of pollutant transport in homogeneous coastal zones with application to Lake Ontario. J. Geohys. Res., 91, 9771-9779.
National Geophysical Data Center, 1996. Bathymetry of Lake Michigan. Report MGG-11.
O'Connor, W.P. and D.J. Schwab, 1994. Sensitivity of Great Lakes Forecasting System Nowcasts to Meteorological Fields and Model Parameters. Proceedings, 3rd International Conference on Estuarine and Coastal Modeling. ASCE Waterway, Port, Coastal and Ocean Division, 149-157.
Pettersen, S. and P.A. Calabrese, 1959. On some weather influences due to warming of the air by the Great Lakes in winter. J. Meteor.,16, 646-652.
Rao, D.B., and T.S. Murthy, 1970. Calculation of the steady-state wind-driven circulation in Lake Ontario. Arch. Meteor. Geophys. Bioklim., A19, 195-210.
Rondy, D.R., 1976. Great Lakes ice cover. In: Limnology of lakes and embayments. Great Lakes Basin Framework Study. Appendix 4. Great lakes Basin Comission, Ann Arbor, Michigan, 105-171.
Rumer, R.R., Wake, A., and S-H. Shieh, 1981. Development of an ice dynamics forecasting model for Lake Erie. Water Resources and Environmental Engineering Res Rep. No 81-1. Department of Civil Engineering, center for Cold Regions Science and Technology, State University of New York at Buffalo.
Saylor, J.H., J.R. Bennett, P.C. Liu, R.L. Pickett, F.M. Boyce, C.R. Murthy, and T.J. Simons, 1981. Water Movements. In 'IFYGL - The International Field Year for the Great Lakes', E.J. Aubert and T.L. Richards eds., Natl. Oceanic and Atmos. Admin., Great Lakes Environ. Res. Lab., Ann Arbor, MI. 247-324.
Saylor, J.H., J.C.K. Huang, and R.O. Reid, 1980. Vortex modes in Lake Michigan. J. Phys. Oceanogr. 10(11), 1814-1823.
Scavia, D. and J.R. Bennett, 1980. Spring transition period in Lake Ontario - a numerical study of the causes of the large biological and chemical gradients. Can. J. Fish. Aquat. Sci., 37, 823-833.

Schmaltz, R., 1996. “Southern boundary experimental forecasts with the NOAA east coast model,” in: Estuarine and Coastal Models IV, eds. M. Spaulding and R. Cheng, ASCE, NY, pg. 442-453.

Schwab, D.J., 1983. Numerical simulation of low-frequency current fluctuations in Lake Michigan. J. Phys. Oceanogr. 13(12), 2213-2224.

Schwab, D.J., 1992. A review of hydrodynamic modeling in the Great Lakes from 1950-1990 and prospects for the 1990’s. In: A.P.C. Gobas and A. McCorquodale (Eds), Chemical dynamics in fresh water ecosystems. Lewis Publ., Ann Arbor, MI, 41-62.

Schwab, D.J., 1989. The use of analyzed wind fields from the Great Lakes marine observation network in wave and storm surge forecast models. Preprint Volume of the 2nd International Workshop on Wave Hindcasting and Forecasting. Environment Canada, Atmos. Env. Service, Downsview, Ont. 257-266.

Schwab, D.J., D. Beletsky, W.P. O’Connor, and D.E. Dietrich, 1996. Numerical simulation of internal Kelvin waves with z-level and sigma level models. In: M.L. Spaulding and R.T. Cheng (eds.), Estuarine and Coastal Modeling, Proceedings of the 4th International Conference. Amer. Soc. of Civil. Eng., New York, NY, 298-312.

Schwab, D.J. and K.W. Bedford, 1994. Initial implementation of the Great Lakes Forecasting System: a real-time system for predicting lake circulation and thermal structure. Water Poll. Res, J. Canada, 29(2/3), 203-220.

Schwab, D.J. and J.R. Bennett, 1987. A Lagrangian comparison of objectively analyzed and dynamically modeled circulation patterns in lake Erie. J. Great Lakes Res. 13(4), 515-529.

Schwab, D.J., J.R. Bennett, P.C. Liu, and M.A. Donelan, 1984. Application of a simple numerical wave prediction model to Lake Erie. J. Geophys. Res., 89(C3), 3586-3589.

Schwab, D.J., A.H. Clites, C.R. Murthy, J.E. Sandall, L.A. Meadows, and G.A. Meadows, 1989. The effect of wind on transport and circulation in Lake St. Clair. J. Geophys. Res., 94(C4), 4947-4958.

Schwab, D.J., G.A. Leshkevich and G.C. Muhr, 1992. Satellite measurements of surface water temperature in the Great Lakes: Great Lakes CoastWatch. J. Great Lakes Res. 18(2), 247-258.

Sheng, Y.P., W. Lick, R.T. Gedney, and F.B. Molls, 1978. Numerical computation of three-dimensional circulation in Lake Erie: a comparison of a free surface model and a rigid lid model. J. Phys. Oceanogr., 8, 713-727.

Simons, T.J., 1980. Circulation models of lakes and inland seas. Can. Bull. if Fisheries and Aquat. Sci., Bull. 203, 146pp.

Simons, T.J., and W.M. Schertzer, 1989. The circulation of Lake Ontario during the Summer of 1982 and the Winter of 1982/83. Sci. Ser. No. 171, Can. Centre for Inland Waters, Burlington, Ontario, 191pp.

Strub, P.T., P.M. Kosro, and A. Huyer, 1991. The nature of cold filaments in the California Current System. J. Geophys. Res., 96(C8), 14743-14768.

Strub, P.T., and T.M. Powell, 1986. Wind-driven surface transport in stratified closed basins: direct versus residual circulation. J. Geophys. Res. 91(C7), 8497-8508.

Stubblefield, B., and J.R. Bennett, 1984. Preliminary report on GLERL’s ice dynamics simulation model. Great Lakes Env. Res. lab., Ann Arbor, Michigan, GLERL Open File Report.

Wang, J., Mysak, L.A., and R.G. Ingram, 1994. A numerical simulation of sea ice cover in Hudson Bay. J. Phys. Oceanogr., 24, 2515-2533.

Ziegler, C.K. and W. Lick, 1988. “The transport of fine-grained sediments in shallow waters,” Environ. Geol. Water Sci., 11, pgs. 123-132.